

Astrophysical cross sections

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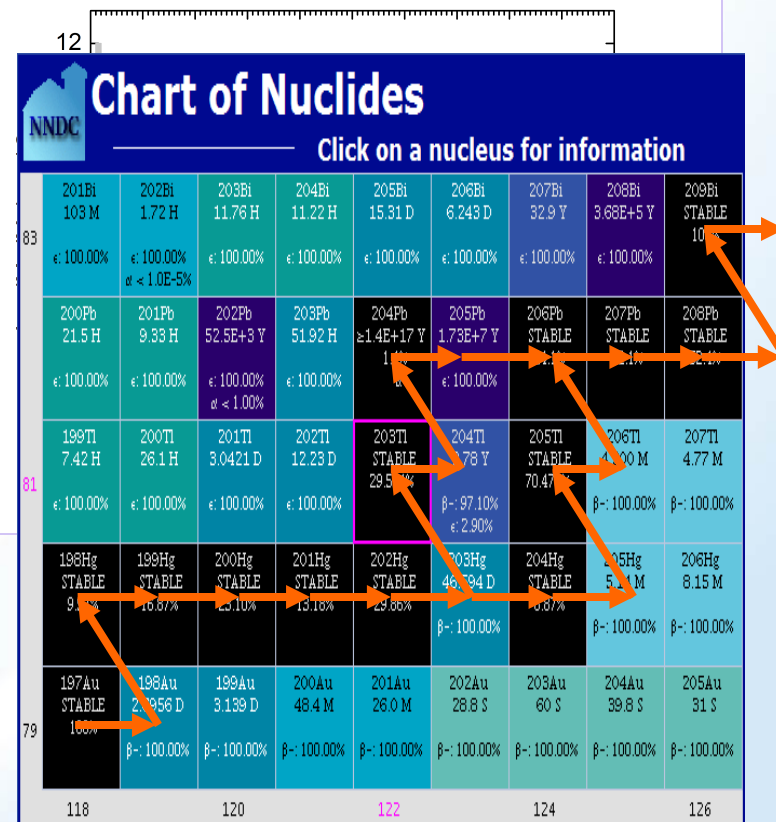
U.S. DEPARTMENT OF
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s-process Nucleosynthesis

- Why do we have stable isotopes with different abundances in solar system???
- Why do we have elemental abundances in solar system and stellar atmosphere???
- The very light nuclei ($^1\text{H} \dots ^7\text{Li}$) are produced during the Big Bang Nucleosynthesis.
- The light nuclei ($^8\text{Be} \dots ^{56}\text{Fe}$) are produced during the explosive burning.
- Valley of Stability nuclei ($^{56}\text{Fe} \dots ^{210}\text{Po}$) are produced by slow neutron capture (s-process).
- Proton rich nuclei ($Z > 26$) are produced by p-process.
- Neutron-rich nuclei ($Z > 26$) and actinides are produced by rapid neutron capture (r-process).

Solar System Elemental Abundances

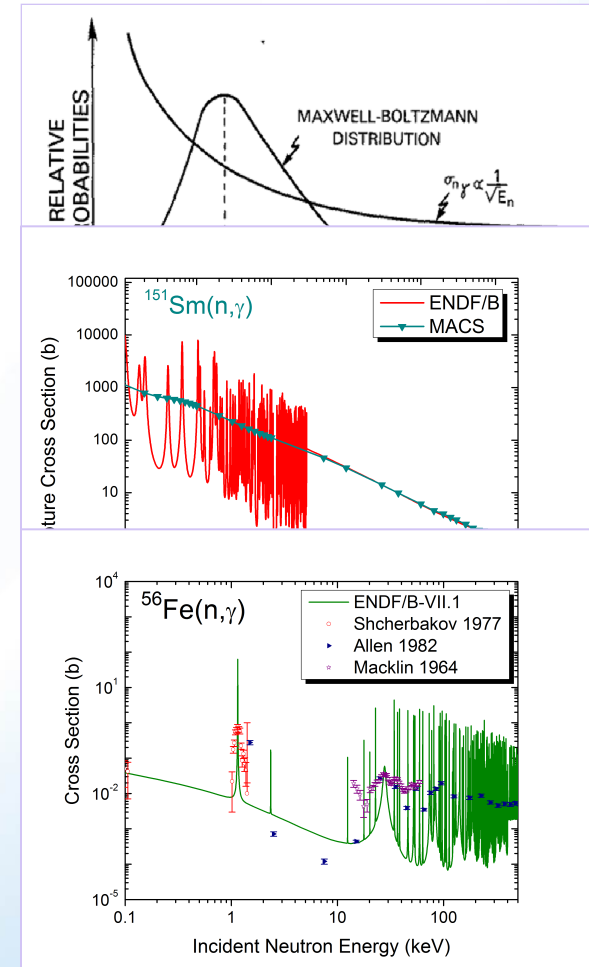


s-process Cross sections

- Slow neutron capture (s-process) takes place in stars. There is no unique s-process temperature, it depends on a particular star (AGB, Red Giant) and ranges from 8 to 90 keV.
- s-process nucleosynthesis Maxwellian-averaged cross sections (MACS) can be expressed as

$$\sigma_{Maxw}(kT) = \frac{2}{\sqrt{\pi}} \frac{(m_1/(m_1 + m_2))^{1/2}}{(kT)^{3/2}} \int_0^\infty \sigma(E_n) E_n^L \exp\left(-\frac{E_n}{kT}\right) dE_n$$

where k and T are the Boltzmann constant and temperature of the system, respectively, and E is an energy of relative motion of the neutron with respect to the target. Here E_n^L is a neutron energy in the laboratory system and m_1 and m_2 are masses of a neutron and target nucleus, respectively.



ENNDF/B-VIII MACS

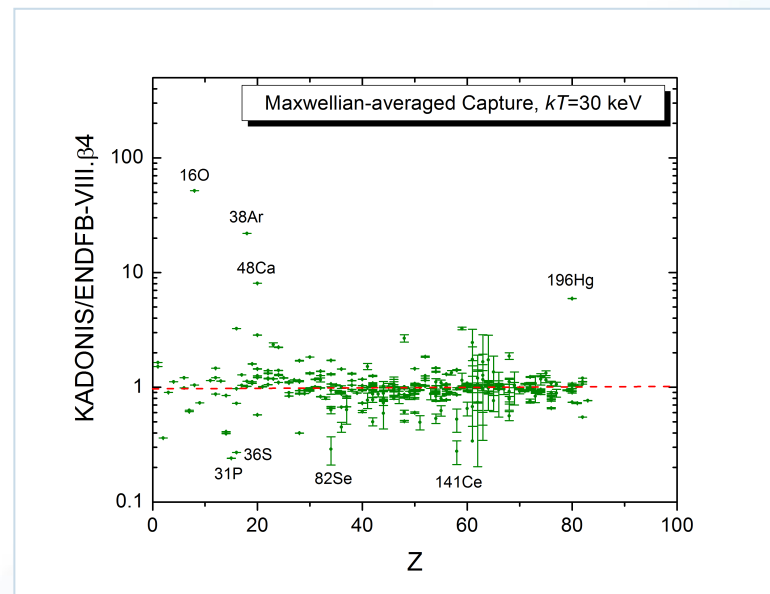
- ENDF/B-VIII.β3 and ENDF/B-VIII.β4 library MACS and their uncertainties have been calculated and compared with corresponding values in Karlsruhe Astrophysical Database of Nucleosynthesis in Stars (KADoNiS).
- KADoNiS (www.kadonis.org) is stellar nucleosynthesis library that consists of ~85% experimental and ~15% theoretical (NON-SMOKER) cross sections.
- KADoNiS values are periodically updated; sometimes new measurements change KADoNiS in dramatic fashion: $^{19}\text{F}(n,\gamma)$ from 5.8(12) mb to 3.2(1) mb in versions 0.0 and 0.3, respectively.
- Some of presently-available KADoNiS 0.3 values are impacted by incorrect ^{197}Au cross sections and will be fixed in 2018.

TABLE 1: ENDF/B-VII.1 [5], ENDF/B-VIII.β4, KADONIS [3] Maxwellian-averaged cross sections and their ratios at $kT=30$ keV. Comments: C-calculated from BNL-325 data [6], T-theoretical data in KADONIS.

Material	ENDF/B-VII.1 (barn)	ENDF/B-VIII.β4 (barn)	KADONIS (barn)	ENDF/B-VII.1/ENDF/B-VIII.β4	KADONIS/ENDF/B-VIII.β4
1-H-1	1.500E-4±1.800E-6	1.500E-4±1.800E-6	2.500E-4±2.000E-5	1.000E+0±1.800E-6	1.666E+0±2.000E-5
1-H-2	1.900E-6±1.240E-7	1.900E-6±1.240E-7	3.000E-6±1.780E-7	1.000E+0±1.780E-7	1.578E+0±2.300E-7
1-Li-5					
2-He-3	2.110E-5	2.110E-5	7.600E-6±6.000E-7	1.000E+0	3.600E+1±6.000E-7
2-He-4					
3-He-3	3.290E-5±1.180E-6	3.290E-5	1.000E+0±1.180E-6	1.000E+0±1.180E-6	9.010E+1±3.000E-6
3-He-4	4.660E-5	4.660E-5	4.200E-5±1.000E-6	1.000E+0	
4-He-7					
4-He-9	9.320E-6±1.860E-6	9.320E-6±1.860E-6	1.040E-5±1.600E-6	1.000E+0±1.600E-6	1.120E+0±1.600E-6
9-B-10	8.310E-4±1.800E-4	1.440E-4	1.220E+0±1.400E-4		
9-B-11	6.620E-4±1.200E-5	6.620E-4±1.200E-5	1.000E+0±1.200E-5	1.000E+0±1.200E-5	
6-C-12	1.620E-5±1.230E-6	1.620E-5±1.230E-6	1.000E+0±1.230E-6	1.000E+0±1.230E-6	
6-C-13					
7-N-14					
7-N-15	8.180E-6±1.450E-6	8.180E-6±1.450E-6	5.800E-6±6.000E-7	1.000E+0±6.000E-7	6.320E+1±4.600E-6
8-O-16	3.170E-5±1.160E-6	3.170E-5	3.800E-5±2.400E-6	1.000E+0±2.400E-6	1.200E+0±4.000E-6
8-O-17	4.780E-6	4.780E-6			
9-F-18	4.370E-5±1.820E-6	4.370E-5±1.820E-6	3.200E-5±1.000E-6	1.000E+0±1.000E-6	3.580E+1±1.800E-6
9-F-19					
10-Ne-20	8.020E-5	8.020E-5	2.100E-5±2.000E-6	1.000E+0±2.000E-6	1.180E+0±2.400E-6
10-Ne-21	1.800E-5±1.370E-6	1.800E-5±1.370E-6	3.700E-5±1.180E-6	1.000E+0±1.180E-6	8.710E+1±3.820E-6
12-Mg-24	3.790E-5±1.180E-6	3.790E-5±1.180E-6	3.500E-5±1.000E-6	1.000E+0±1.000E-6	1.210E+0±4.000E-6
12-Mg-25	3.200E-5±1.310E-6	3.200E-5±1.310E-6	4.400E-5±1.800E-6	1.000E+0±1.800E-6	1.360E+0±1.800E-6
12-Mg-26	8.610E-5±1.620E-5	8.610E-5±1.620E-5	1.200E-4±9.000E-6	1.000E+0±9.000E-6	1.660E+0±1.800E-5
13-Al-27	3.310E-5±1.610E-6	3.310E-5±1.610E-6	3.740E-5±1.500E-6	1.000E+0±1.500E-6	1.130E+0±2.600E-6
14-Si-28	3.610E-5±1.000E-6	3.610E-5±1.000E-6	1.420E-5±1.300E-6	1.000E+0±1.300E-6	2.580E+1±1.310E-6
14-Si-29	7.770E-5±1.830E-6	7.770E-5±1.830E-6	6.900E-5±1.600E-6	1.000E+0±1.600E-6	8.470E+1±1.000E-5
14-Si-30	4.680E-5±1.520E-6	4.680E-5±1.520E-6	1.020E-5±1.500E-6	1.000E+0±1.500E-6	4.600E+1±1.600E-5
15-P-31	7.240E-5	7.240E-5	3.740E-5±1.900E-6	1.000E+0	2.400E+1±1.900E-6
16-S-32	1.640E-5	1.640E-5	4.100E-5±2.500E-6	1.000E+0	7.000E+0±2.500E-6
16-S-33	2.280E-5	2.280E-5	7.400E-5±1.800E-6	1.000E+0	3.200E+0±1.800E-6
16-S-34	2.320E-5	2.320E-5	2.500E-5±1.100E-6	1.000E+0	9.700E+0±1.000E-6
16-S-36	6.330E-6	6.330E-6	1.710E-6±1.400E-6	1.000E+0	2.770E+1±1.400E-5
17-Cl-35	7.540E-5	7.540E-5	7.600E-5±2.100E-6	1.000E+0	1.200E+0±2.100E-6
17-Cl-37	2.040E-5	2.040E-5	2.130E-5±1.700E-6	1.000E+0	1.040E+0±1.700E-6
18-Ar-36	8.840E-5	8.840E-5	9.000E-5±1.500E-5	1.000E+0	1.020E+0±1.500E-5
18-Ar-38	1.700E-4	1.700E-4	3.000E-5±1.500E-5	1.000E+0	1.100E+0±1.500E-5
18-Ar-40	2.280E-5	2.280E-5	2.540E-5±2.100E-6	1.000E+0	1.130E+0±2.100E-6
19-K-39	1.060E-2	1.060E-2	1.100E-2±4.000E-4	1.000E+0	2.200E+1±4.000E-4
19-K-40	1.940E-2	1.940E-2	3.100E-2±1.700E-3	1.000E+0	1.600E+0±1.700E-3
19-K-41	2.300E-2±1.060E-16	2.300E-2±1.060E-16	3.100E-2±1.700E-3	1.000E+0±1.700E-3	1.600E+0±1.700E-3
20-Ca-40	5.130E-5	9.970E-5	3.700E-5±1.400E-6	1.000E+0	5.700E+1±1.400E-6
20-Ca-42	1.240E-5	1.240E-5	1.500E-5±2.100E-6	1.000E+0	1.200E+0±2.100E-6
20-Ca-43	3.530E-5	3.530E-5	5.100E-5±2.600E-6	1.000E+0	1.400E+0±2.600E-6
20-Ca-44	7.740E-5	7.740E-5	9.400E-5±1.300E-5	1.000E+0	1.200E+0±1.300E-5
20-Ca-46	1.860E-5	1.860E-5	3.500E-5±3.000E-6	1.000E+0	2.800E+0±3.000E-6
20-Ca-48	1.060E-4	1.060E-4	8.700E-5±9.000E-6	1.000E+0	8.000E+0±9.000E-6
21-Sc-45	6.840E-2	6.840E-2	1.000E-2±1.000E-3	1.000E+0	1.000E+0±1.000E-3
21-Sc-46	1.310E-2	1.310E-2	1.600E-2±1.700E-3	1.000E+0±1.700E-3	1.200E+0±1.700E-3
21-Sc-47	4.870E-2±1.450E-3	4.870E-2±1.450E-3	6.440E-2±1.700E-3	1.000E+0±1.700E-3	4.320E+0±1.700E-3
22-Ti-48	2.600E-2±7.040E-9	2.600E-2±7.040E-9	3.100E-2±1.000E-3	1.000E+0±1.000E-3	1.200E+0±1.000E-3
22-Ti-49	1.500E-2±1.960E-6	1.500E-2±1.960E-6	2.210E-2±2.100E-3	1.000E+0±2.100E-3	1.400E+0±2.100E-3
22-Ti-50	3.040E-3±1.800E-12	3.040E-3±1.800E-12	3.600E-3±2.400E-4	1.000E+0±2.400E-4	1.180E+0±2.400E-4
23-V-50					
23-V-51	2.130E-2	2.130E-2	5.000E-2±9.000E-3	1.000E+0	2.300E+0±9.000E-3
23-V-52	3.210E-2	3.210E-2	3.800E-2±4.000E-3	1.000E+0	1.190E+0±4.000E-3
24-Cr-50	3.830E-2	3.830E-2	4.900E-2±1.300E-3	1.000E+0	1.260E+0±1.300E-3
24-Cr-52	7.990E-3±1.271E-4	7.990E-3±1.271E-4	8.800E-3±2.300E-3	1.000E+0±2.300E-3	1.100E+0±2.300E-3
24-Cr-54	2.600E-2	2.600E-2	3.800E-2±1.000E-3	1.000E+0	1.400E+0±1.000E-3
24-Cr-56	4.780E-3	4.780E-3	6.700E-3±1.600E-3	1.000E+0	1.400E+0±1.600E-3
24-Cr-58	3.200E-2±1.200E-3	3.200E-2±1.200E-3	3.600E-2±1.200E-3	1.000E+0±1.200E-3	1.100E+0±1.200E-3
26-Mn-54	2.160E-2±1.600E-3	2.160E-2±1.600E-3	2.900E-2±1.300E-3	1.000E+0±1.300E-3	1.300E+0±1.300E-3
26-Mn-55	1.130E-2±1.180E-3	1.130E-2±1.180E-3	1.700E-2±5.000E-4	1.000E+0±5.000E-4	8.300E+1±5.000E-4
26-Mn-56	1.000E-2±6.000E-3	1.000E-2±6.000E-3	4.000E-2±2.400E-3	1.000E+0±2.400E-3	7.900E+1±2.400E-3
26-Mn-58	1.970E-2	1.970E-2	1.330E-2±7.000E-4	1.000E+0	1.400E+0±7.000E-4
27-Co-58M	2.020E-1	2.020E-1	1.000E-1	1.000E+0	
27-Co-59M	6.440E-2	6.440E-2	3.900E-2±2.700E-3	1.000E+0	1.600E+0±2.700E-3
27-Co-60	3.440E-2	3.440E-2	3.700E-2±1.800E-3	1.000E+0±1.800E-3	1.140E+0±1.800E-3
28-Ni-58	3.390E-2±1.780E-3	3.390E-2±1.780E-3	3.700E-2±1.400E-3	1.000E+0±1.400E-3	1.100E+0±1.400E-3
28-Ni-59	6.960E-2	6.960E-2	8.700E-2±1.400E-2	1.000E+0	1.200E+0±1.400E-2
28-Ni-60	2.000E-1±1.900E-5	2.000E-1±1.900E-5	2.900E-1±1.200E-5	1.000E+0±1.200E-5	1.400E+0±1.200E-5
28-Ni-61	9.030E-2	9.030E-2	8.200E-2±3.000E-3	1.000E+0	8.810E+1±3.000E-3
28-Ni-62	2.380E-2	2.380E-2	2.700E-2±1.600E-3	1.000E+0	9.340E+1±1.600E-3
28-Ni-64	2.010E-2	2.010E-2	1.000E-2±7.000E-4	1.000E+0	3.990E+1±7.000E-4
29-Cu-63	7.180E-2	7.180E-2	5.600E-2±2.000E-3	1.000E+0	9.300E+1±2.000E-3
29-Cu-65	3.920E-2	3.920E-2	2.900E-2±1.100E-3	1.000E+0	8.000E+1±1.100E-3
30-Zn-64	6.100E-2	6.100E-2	5.900E-2±2.000E-3	1.000E+0	9.670E+1±2.000E-3
30-Zn-66	1.600E-1	1.600E-1	1.620E-1±1.200E-2	1.000E+0	1.140E+0±1.200E-2
30-Zn-68	3.640E-2	3.640E-2	3.300E-2±1.500E-3	1.000E+0	9.610E+1±1.500E-3
30-Zn-70	1.160E-1	1.160E-1	1.570E-1±1.500E-2	1.000E+0	1.320E+0±1.500E-2
30-Zn-72	2.080E-2	2.080E-2	1.930E-2±5.400E-3	1.000E+0	9.280E+1±5.400E-3
30-Zn-74	1.170E-2	1.170E-2	2.190E-2±1.200E-3	1.000E+0	1.860E+0±1.200E-3
31-Ga-69	1.190E-1	1.190E-1	1.300E-1±3.000E-3	1.000E+0	1.170E+0±3.000E-3
31-Ga-71	1.230E-1	1.230E-1	1.230E-1±2.500E-3	1.000E+0	1.000E+0±2.500E-3
32-Ge-70	8.930E-2	8.930E-2	8.800E-2±3.500E-3	1.000E+0	9.970E+1±3.500E-3
32-Ge-72	5.300E-2	5.300E-2	7.300E-2±1.700E-3	1.000E+0	1.380E+0±1.700E-3
32-Ge-73	2.100E-1	2.100E-1	2.400E-1±4.700E-2	1.000E+0	1.160E+0±4.700E-2
32-Ge-74	4.540E-2	4.540E-2	3.700E-2±1.500E-3	1.000E+0	8.200E+1±1.500E-3
32-Ge-76	1.700E-2	1.700E-2	2.150E-2±1.800E-3	1.000E+0	1.270E+0±1.800E-3
33-Ar-73					
33-Ar-74	1.500E-1	1.500E-1			
33-Ar-75	4.500E-1	4.500E-1	3.620E-1±1.900E-2	1.000E+0	8.040E+1±1.900E-2
34-Ge-74	2.080E-1	2.080E-1	2.710E-1±1.500E-2	1.000E+0	1.300E+0±1.500E-2
34-Ge-76	9.580E-2	9.580E-2	1.640E-1±2.800E-3	1.000E+0	2.710E+0±2.800E-3
34-Ge-77	4.450E-1	4.450E-1	4.180E-1±1.700E-2	1.000E+0	9.400E+1±1.700E-2
34-Ge-78	9.970E-2	9.970E-2	6.010E-2±2.900E-3	1.000E+0	6.630E+1±2.900E-3
34-Ge-79	4.150E-1	4.150E-1	2.650E-1±1.400E-2	1.000E+0	6.340E+1±1.400E-2
34-Ge-80	3.930E-2	3.930E-2	4.200E-2±1.500E-3	1.000E+0	9.600E+1±1.500E-3
34-Ge-82	3.110E-2	3.110E-2	9.000E-3±4.000E-4	1.000E+0	2.800E+1±4.000E-4
34-Ge-83	6.870E-1	6.870E-1	6.220E-1±2.500E-2	1.000E+0	9.000E+1±2.500E-2
35-Sr-81	2.290E-1	2.290E-1	2.300E-1±7.000E-3	1.000E+0	1.000E+0±7.000E-3
36-Kr-78	4.710E-1	4.710E-1	3.210E-1±1.600E-2	1.000E+0	1.010E+0±1.600E-2
36-Kr-80	4.790E-1	4.790E-1	2.670E-1±1.400E-2	1.000E+0	9.370E+1±1.400E-2
36-Kr-82	1.030E-1	1.030E-1	9.800E-2±3.600E-3	1.000E+0	8.740E+1±3.600E-3
36-Kr-83	2.470E-1	2.470E-1	2.450E-1±1.100E-2	1.000E+0	9.100E+1±1.100E-2
36-Kr-84	2.640E-2	2.640E-2	3.800E-2±2.400E-3	1.000E+0	1.400E+0±2.400E-3
36-Kr-85	1.230E-1	1.230E-1	5.800E-2±4.900E-3	1.000E+0	4.490E+1±4.900E-3
36-Kr-86	5.070E-1	5.070E-1	3.400E-1±1.500E-2	1.000E+0	6.710E+1±1.500E-2
37-Rb-85	2.820E-1	2.820E-1	2.540E-1±7.000E-3	1.000E+0	1.120E+0±7.000E-3

ENNDF/B-VIII.β4 MACS

- There are noticeable differences between KADoNiS and ENDF/B-VIII.b4 libraries for light and medium nuclei.
- ^1H and ^3He experience significant deviations due to differences between center of mass and lab system cross section values.
- Other deficiencies could be separated into three groups:
 - ^{31}P , ^{36}S and ^{196}Hg KADONIS values are based on a single recent measurement.
 - Due to lack of experimental data theoretical values were adopted for ^{38}Ar , ^{82}Se , ^{141}Ce .
 - Deficiencies in ^{16}O and ^{48}Ca originate from the old or insignificant for integral tests ENDF evaluations and coverage problems in EXFOR database.

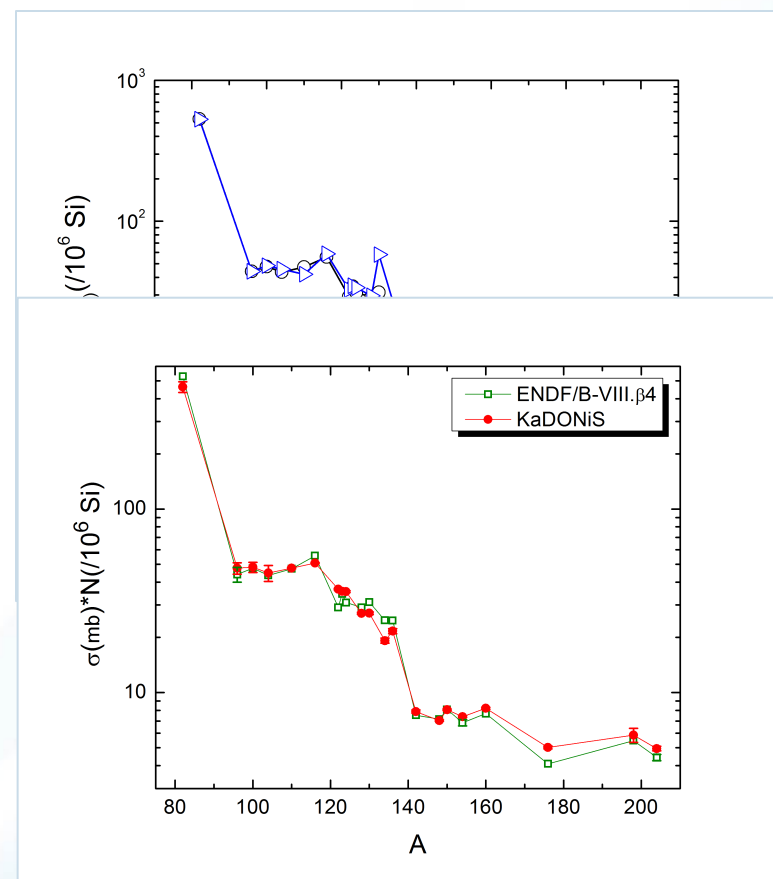


Stellar Nucleosynthesis

- In s-process nucleosynthesis, the product of neutron-capture cross section (at 30 keV in mb) times solar system abundances (relative to Si = 10^6) as a function of atomic mass should be constant for s-process only equilibrium nuclei

$$\sigma_A N_A = \sigma_{A-1} N_{A-1} = \text{const}$$

- Visual inspection of the figures indicates two local equilibrium and ledge-precipice break at $A \sim 138$ for the ENDF libraries fit.
- Strong astrophysical potential of the ENDF/B-VIII.β4 library

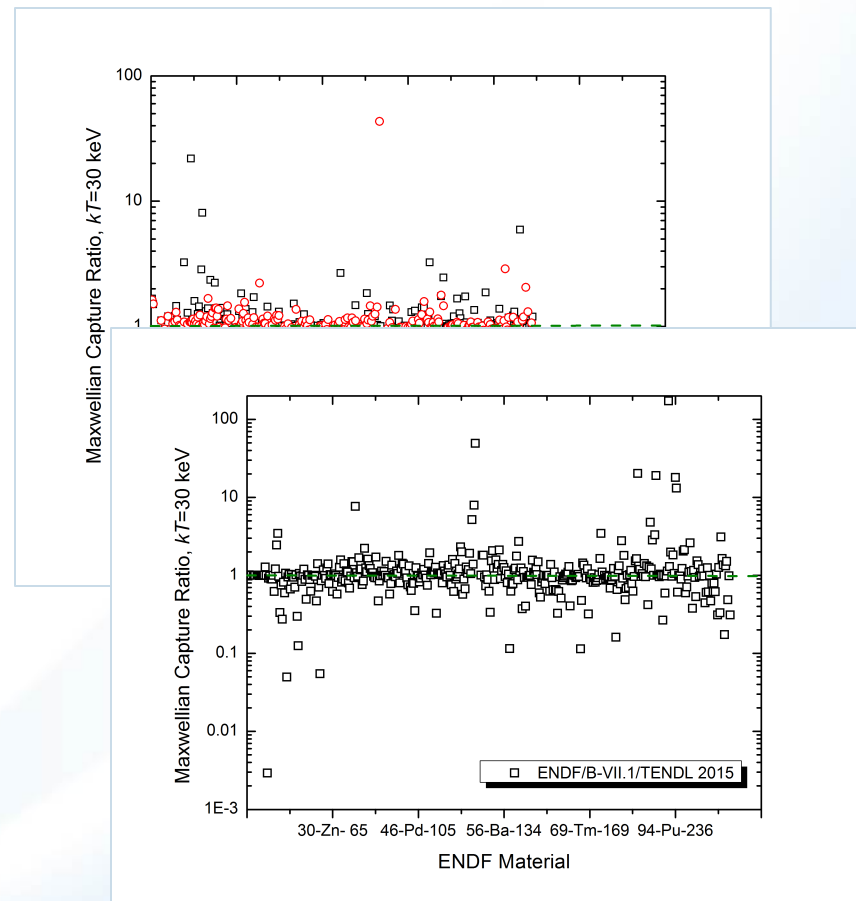


TENDL 2015 vs. ENDF/B-VII.1

- In September 2016 A. Sonzogni has suggested to evaluate both libraries using Maxwellian-averaged cross sections in KADoNiS.
- A few comments on TENDL 2015:
 - Overall neutron library size: 14.8 GB
 - Doppler-broadened neutron library, 0.1%: 237 GB
 - Processing time on Windows PC: 1-1.5 days
- More on TENDL 2015: 2809 materials. It is missing ^{129,130,131,135}I that exist in ENDF/B-VII.1.
- **TENDL has astrophysical adjustments, while ENDF is not.**
- ENDF/B-VII.1 is definitely better for Sr, Te, Sm and Hg. No difference for major actinides. In other cases TENDL 2015 is often better.
- TENDL 2015 is better matched with theoretical values in KADONIS (NON-SMOKER calculations).

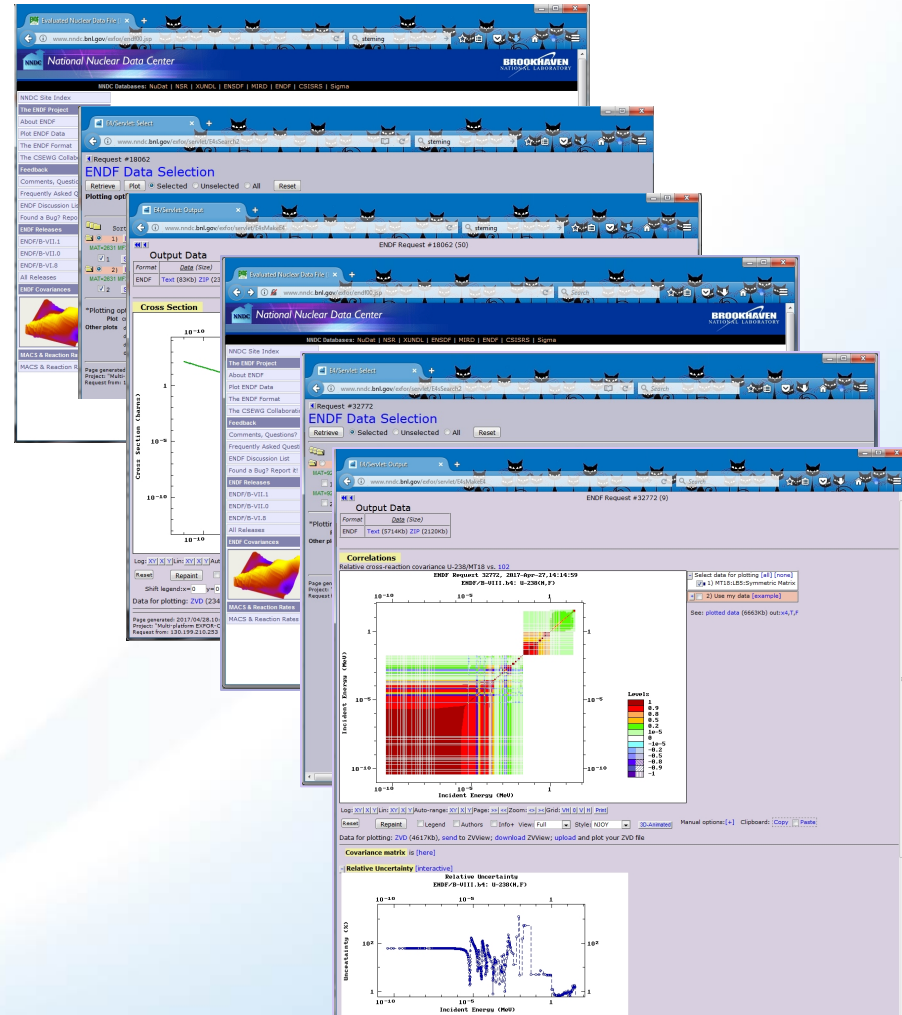
TENDL 2015 vs. ENDF/B-VII.1

- NNDC style calculations of MACS were produced; INTER results listed in TENDL 2015 were ignored as not very reliable.
- Comparison with KADoNiS.
- Comparison of two libraries Maxwellian-averaged cross sections, $kT=30$ keV.
- Current values could be helpful Identification potential deficiencies in both libraries.
- The good news that we have time to improve ENDF/B and KADoNiS is not always perfect.



ENDF/B-VIII.β4 Web Interface

- ENDF/B-VIII.β4 is available at the NNDC website:
<http://www.nndc.bnl.gov/endl>
- Powerful tool for ENDF/B-VIII.β4 quality assurance.
- Example of $^{56}\text{Fe}(n,\gamma)$ retrieval for ENDF/B-VII.1 and ENDF/B-VIII.β4.
- Example of $^{238}\text{U}(n,f)$ covariance retrieval for ENDF/B-VIII.β4.
- Collaborative effort with Viktor Zerkov (IAEA).



Conclusions & Outlook

- There is a very strong astrophysical potential of ENDF/B-VIII.β4 library.
- Several deficiencies have been identified in ENDF/B-VIII.β3 and ENDF/B-VIII.β4 releases.
- ENDF/B-VIII developers should not be intimidated by KADoNiS or TENDL cross sections. It is important to produce its own product.
- Do we need calculations of RI, Westcott factors, ^{252}Cf and thermal cross sections using ENDF/B-VIII library?
- Do we need any comparison with TENDL?
- Any missing in EXFOR nuclear astrophysics data sets could be processed at NNDC if necessary.